MEASURING SUSTAINABILITY AND URBAN DATA OPERATIONALIZATION

An integrated computational framework to evaluate and interpret the performance of the urban form.

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Abstract. With rapid urbanization, the necessity for sustainable development has skyrocketed, and sustainable urban development is a must. Recent advances in computing performance of urban layouts in real-time allow for new paradigms of performance-driven design. As beneficial as utilizing multiple layers of urban data may be, it can also create a challenge in interpreting and operationalizing data. This paper presents an integrated computational framework to measure sustainability, operationalize and interpret the urban form's performance data using generative design methods, novel performance simulations, and machine learning predictions. The performance data is clustered into three pillars of sustainability: social, environmental, and economical, and it is followed with the performance space exploration, which assists in extracting knowledge and actionable rules of thumb. A significant advantage of the framework is that it can be used as a discussion table in participatory planning processes since it could be easily adapted to interactive environments.

Keywords. Generative design; data interpretation; urban sustainability; performance simulation; machine learning.

1. Introduction

Given the changes the world has undergone over the last decades, the necessity for sustainable development has skyrocketed. Yet, to balance social equity and economic potential with the environmental-focused design is quite a lofty challenge. The urban agendas are fostering the call for a more sustainable development followed by tools for action. Besides, many attempts towards quantifying quality in the domain of sustainable development are ongoing.

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Many researchers have already made substantial contributions to this discussion (Cotgrave & Riley, 2013), presenting answers for how sustainable a project can be and what impact such a sustainable project has on the world. The traditional evaluation method of urban spaces is either by analyzing and interpreting secondary data such as open-source data or generating data from surveys and focuses on humans behaviors and more on an individual level (Marans & Stimson, 2011). Similarly, there have been several checklists on measuring sustainability introduced and assisted in urban design.On the other hand, frameworks that can estimate the impact of changing elements within the urban systems are in high demand (Achary et al., 2017). They make the planning process more manageable, where designers combine their design instinct with performance data. In this context, data mining, generation, and analysis gain more significance, especially in early design phases (Nembrini, 2012). By providing an enormous number of analysis parameters that influence specific performance metrics, one can increase a designer's capacity to achieve design goals based on urban performance. The recent advances in computing urban layouts‘ performance have opened new paradigms of performance-driven and evidence-based urban design. Applying performance-driven design could create a workflow that allows us to have overall feedback on the design's performance and have an iterative process of advancements based on the formation of ideas and their evaluations (Lawson, 2006). Collating digital computation and humans' creativity offers the possibility to manage the urban system's complexity and allows the ability to test vast design options in a short manner of time. Interpreting urban data, either mined from open source data platforms, generated from simulations, or different computational methods would assist the early stages of design as guidance towards urban design. To operationalize data, understand why a design performs in the way it does, and avoid mistakes in the planning process, a sound understanding between the design parameters and the different performance criteria is crucial (Bielik et al., 2019). This understanding could lead to extracting knowledge on actionable guidance for designers. However, analyzing many aspects of an urban space leads to several data layers and an almost unmanageable amount of information. As beneficial as having many urban data layers might be, it also creates a challenge in finding relevant datasets (Ribeiro, 2015). This way, data can also be confusing if the approaches toward dimensionality reduction and data interpretation are inadequate. Even more, impracticable data can be deficient because quantifying a design's performance does not necessarily provide insight or guidance on why it performs better or worse and how to improve the urban layout. More research is needed on quantifying urban sustainability in new urban development projects, as well as filtering the information and clustering it in an operationalizable format, which is interpretable and easy to understand by all the stakeholders. Additionally, extracting knowledge on actionable guidance for designers based on the performance data would contribute to the early stages of sustainable urban planning. In response to the research gaps, this paper presents an integrated computational framework to operationalize and interpret the performance of urban forms; Which algorithmically builds a generative urban design model, adjusts methods to quantify urban performance in each pillar of sustainability in real-time, and it correlates the input design parameters with the outputs that indicate the performance.

2. Architecture of the Framework

The framework uses the state of the art methodologies on urban design: algorithmic urban planning, generative design methods, performance simulations, agent-based urban dynamic models, and machine learning predictions. Solution space exploration and performance data analysis follow each calculation, from where data is interpreted, and general rules of thumb derived. The primary work environment where the framework is implemented is Rhino and its visual programming language Grasshopper environment. The framework is consisted out of three parts the algorithmic generation of urban form, the evaluation part where existing methods are adapted, extended, and aggregated; and the data analysis part.

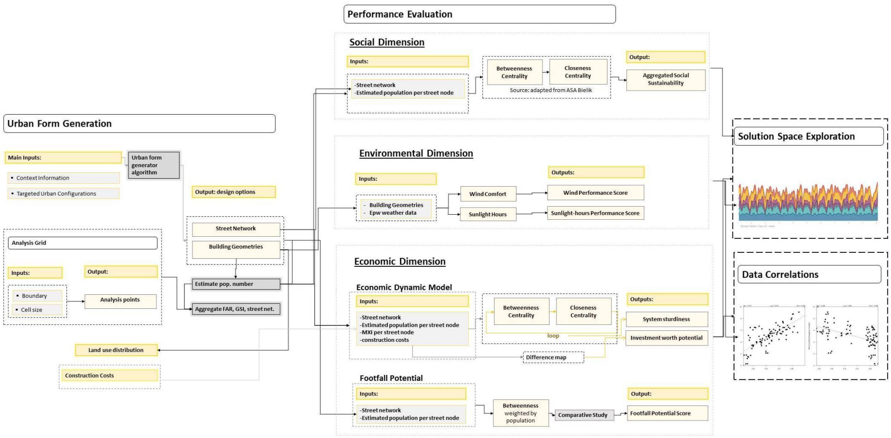

Figure 1. Architecture of the framework.

2.1. THE GENERATIVE DESIGN ALGORITHM AND PRINCIPLES

The first part of the framework is the generation of the urban form. This paper employs a generative design method, which from the algorithmic process and specific input parameters enables exploring different complex urban forms. As input parameters, the generative model uses the street network orientation and the density indicators because density has been a relevant metric in urbanism since the small settlements' formation until their evolutions into villages or cities. In the book 'The Radiant City,' Le Corbusier et al. (1967) state that cities need a specific density for the machine-age man, which would provide short travel time between housing, jobs, and other attractive locations in the city. Furthermore, Jan Gehl (2010) states that urban density is a critical factor in understanding how cities function. With COVID-19, the global pandemic faced in 2020, the debate around whether highly dense areas and compact cities are the goals of urban planners comes into question. Berghauser Pont and Haupt, in their Book

Spacematrix: Space Density and urban form, present several density metrics that explore urban density as crucial information in designing and reading the city and categorize the building structures into different categories of urbanity. The density metrics that it elaborates on are the FAR floor area ratio and the GSI Ground space index.Regarding street network orientation, Geoff Boeing - a researcher in urban planning- (2019), indicates that the street network orientations assist in understanding the histories of places' urban development. Furthermore, he claims that street network orientation is also helpful when evaluating the current network system. Based on the orientation of streets planners, it could be critical and explore further design proposals. Given the aforementioned, the algorithm that generates design options uses the street network orientation, Ground Space Index (GSI), and Floor Area Ratio (FAR). The street network snaps to the existing streets by creating superblocks. Within those areas regular grid of street nodes are generated, the main streets rotate for 20 degrees after each iteration, offering the option to explore various street network orientation. While the size of the footprint(amount of space that it takes in the plot) is based on the targeted Ground Space index, The Floor Area ratio is based on the buildings' height.The street network segments are categoried based on their closest direction out of four main ones (North-South, Northwest -Southeast, West-East, Southwest-Northeast), and their meter length presented in % per each design design case, which output 4 numbers that indicates the amount of street lenghts in the corresponding orientation. The overall density and street network are validated after the generation; the information is aggregated in the analysis grid. The overall average is used as an aggregated indicator, which is used to correlate the output performance.

2.2. PERFORMANCE INDICATORS DERIVATION ON THE THREE PILLARS OF SUSTAINABILITY

The indicators are categorized in the three pillars of sustainability: social, environmental, and economical. The study focuses on evaluation metrics that highly depend on the urban form. This way, the designer can contribute as much as they can towards finding the best performing solution.

2.2.1. Social Sustainability Evaluation Method

The social dimension of sustainability states a social organization system that tackles the equalities and relations between humans. Societies do more than only exist in space (Hillier B. H., 1984). They act and interact with each other. Precisely those mutual relationships between individuals and human interactions make their behaviors social (Weber, 1991). An essential social factor of equality that depends on the built environment is equal access. Urban issues that reflect unequal accessibility can lead to consequences that affect the whole city as a complex system, such as social segregation or exclusions. Consequently, it is crucial to keep in mind the accessibility while designing. This study adapts space syntax metrics with demographic data to measure social segregation and access to significant quarters of the designed urban layout. Some parts of the city are livelier, based on their connectivity properties, which can be considered spots with high interaction potential since more people frequent them. To see how integrated people to other society are, one can measure the accessibility of every individual to the lively spots. This analysis can be done using street network represented in a graph. A method that estimates the pedestrian flows and calculates the access to the lively areas is presented from Bielik, et al. (2018). This paper uses the same approach, and just it first estimates the population number based on the building geometries. And it uses this information as a weight in the betweenness centrality calculation. The results are on the street network, so the information is aggregated in an analysis grid. The process is repeated for all the generated cases, and from the global values, based on Jenks natural breaks, five category bounds are defined. The sum of favorable locations is used as an aggregated indicator in social sustainability.

2.2.2. Environment Sustainability Evaluation Method

Lately, with the threat of climate change, and the significant impact of the built environment on climate, microclimate analysis is a must in the early stages of design. The geo-located wind speeds and solar radiation are the only microclimatic parameters that depend widely on urban planning (Reiter, 2010). Hence, this study focuses on sunlight hours and wind comfort performance of the urban form. In order to have instant feedback on the performance, the research uses pre-trained machine learning models of CIL (City Intelligence Lab of AIT) to predict the microclimate analysis. The ML model that predicts the wind comfort is trained on computational fluid dynamics CFD simulations. Based on each point's wind factors, the results are categorized on the Lawson Wind Comfort Criteria. Because of the high wind speed, the areas exposed to the last two categories are considered dangerous, and the rest is safe and provides pedestrian comfort in terms of wind. The percentage of the safe regions is used as an aggregated performance indicator for the design option. This process is repeated for all design cases, the overall results are remapped in a scale from 0 to 10 (where the higher the number the more pedestrian comfort offers the design). The sunlight hours similarly are predicted using ML models of Infrared. The threshold of vulnerable spots and good performing areas is set by defining the place's purpose and the corresponding sunlight hours demand (while people might need a minimum of two hours of sunlight, some vegetation types demand over six hours). In this study, we set the threshold to 5,5 hours. The areas that are exposed to less than 5,5 hours of daily sunlight are considered vulnerable. The amount in % of the good performing spots is used as a performance indicator. Similarly as in the wind comfort, the process is repeated for each case, and the result values are remapped in a range from 0 to 10.

2.2.3. Economic Sustainability Evaluation Method

The economic potential of a designed option is tightly related to the time dimension. Agent-based models and analytical economic models cannot be integrated easily into the design process (Karimi, 2012). However, combining existing workflows, this research puts together a hypothetical economic dynamic model to understand how resilient the city as a complex system is. Additionally, it gives insights on the investment worth the potential of a spot. The workflow is consisted out of: spacematrix and MXI; this information is brought as destination weight to the evolved configurationally properties of streets by Bielik et al. (2019), creating an endless cycle of simulating the pedestrian movement flows and accordingly the land use distribution. From this model, this research outputs two performance indicators: The worth investment potential and the system sturdiness. For the investment worth potential, the dynamic model's first and last stage is used to create a difference map. This difference map is showing if the place would become more attractive or less in time. Afterward, the results are overlapped with the constructions costs based on the landuse of the building. Overall results in the grid are summed up, and in one single number. The same process is repeated for every case, and the overall performance indicators are remapped in a scale from 0 to 10. On the other hand, the system sturdiness tracks the number of iterations that there are still changes in the system. If the number is higher it means that that the system changes slow, and it is more robust. The list of the performance indicators of each case is remapped in a scale from 0 to 10. Besides the dynamic model, the research employs an indicator that can be used as a proxy to choose locations with high economic potential, which is the footfall potential. It estimates the pedestrians in each street node, using betweenness centrality. As aggregated indicator, is used the fraction between the maxima in the site with the overall global maxima in the context. The results of each case are stored on a list, and remapped in a scale from 0-10.

3. Application of the Framework and Performance Space Exploration

The framework is applied in a new development site in Vienna. The locations' significance lies in its connectivity with Vienna and a large amount of greenery in the surrounding. Based on Vienna Sustainable Development Strategies, the site's development should be based on its residents' social equalities, offer them job opportunities, a healthy environment, and sustainable development. Therefore the location is considered a good base for the study. Based on the given floor area ratio, ground space index, and the street network rotation, hundred and one cases are generated. As aforementioned in the methodology part, this step is followed by elaborating the geometrical solution space and performance space in each performance indicator.

3.1. SOCIAL DIMENSION PERFORMANCE SPACE

3.1.1. ASA - Aggregated Social Sustainability

As an outcome, the aggregated social sustainability (ASA) value seems to be tightly related to street network configurations. From the correlations of ASA value with the street orientation, in general, we can see that the higher the amount of northwest-southeast and the southwest-northeast oriented street amount, the value of the integrity is lower. And oppositely, if the streets are oriented in north-south or west-east, the ASA value is high. From the context, we can also associate that the existing network is dominating in the north-south and west-east orientation. This street orientation matching while designing could be a basis to draw a rule of thumb to inform the design decisions.

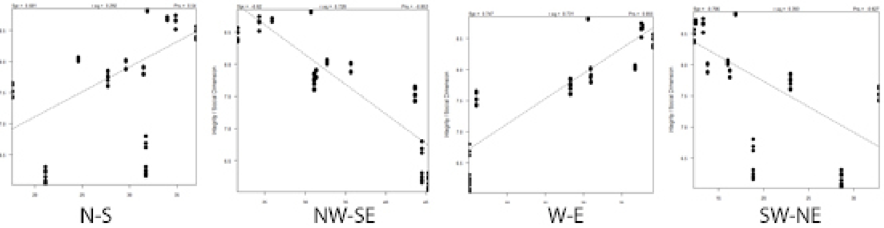

Figure 2. Correlation of the aggregated social sustainability(ASA) with the four street network orientations.

3.2. ENVIRONMENTAL DIMENSION PERFORMANCE SPACE

3.2.1. Wind Comfort

Concerning the correlation outcomes, there is seen a medium positive linear association between the pedestrian comfort in terms of wind and the floor area ratio of the design (see fig.2 left). There is a small linear association between the pedestrian comfort in terms of wind and the design's floor space index. This correlation does not necessarily indicate that the higher the floor area ratio, the higher the wind comfort, and it does not imply causation. An explanation of this is that the higher the building's volume creates more wind shadow, which could lower the wind speed and offer higher pedestrian comfort. Besides, it is seen from the performance, open spaces tend to be less comfortable for pedestrians, and most of the time, dangerous. So, in a sustainable urban layout, there should be a good balance and composition between built and non-built spaces.

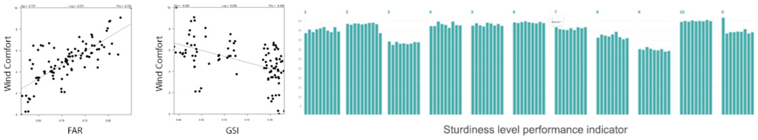

Figure 3. Left: Correlation of the wind comfort with the density metrics (FAR and GSI); Right:Sturdiness level performance indicator grouped by the street type (indicated above the grouped bar charts).

3.2.2. Sunlight Hours

The highest R-squared value comes from the correlation of the aggregated sunlight hour performance indicator with the floor area ratio. There is a very low association between the design option's sunlight performance and the design's floor space index. Similarly, between sunlight hours and the street network orientations, there is no clear correlation. On the other hand, the scatterplot shows a low negative linear association between the design option's sunlight performance and the design's floor area ratio. A high floor area ratio, causing a lack of sunlight, can be argued that more shadow is created from high-rise buildings.

3.3. ECONOMIC DIMENSION PERFORMANCE SPACE

3.3.1. System Sturdiness

Based on the correlation's outcome, one can indicate that the built structure has a relation with the system sturdiness. With a 0.35 R-squared, there is seen a moderate negative correlation between the floor area ratio and the design's sturdiness level. On the other hand, there is a positive correlation between the ground space index with the system sturdiness. It might have happened since the building volumes are used to estimate the population number, and this data was aggregated in the street network and used as an initial weight. On the other hand, the street network has a close relationship with the system sturdiness level; this can also be seen in Figure 3, right side, where the design options with the same street network have very similar system sturdiness levels. However, the street orientation perhaps doesn't capture all factors affecting sturdiness, and further parameters should be tracked from the urban form. It worth to mention, that further research is needed to understand the performance of the system sturdiness level.

3.3.2. Investment worth potential

There is seen a moderate negative relationship between the floor space index and the investment worth potential. Based on the outcome, built structures with higher construction costs should be allocated in areas where the value remains stable or appreciates. To reduce risk, the build structures with lower construction costs should be allocated in worse-performing areas. However, this model does not consider market values, which would have increased the work's complexity, but it would doubtlessly also augment the workflow.

3.3.3. Footfall Potential

The footfall potential indicator doesn't have a strong linear correlation with the spatial configurations (FAR, GSI, Street network orientation). However, based on the grouped bar graphs, the same street network design cases perform very similarly in terms of footfall potential. To understand what is precisely is causing the changes, further studies can be done. Multiple linear regression models can be applied to correlate the performance data further by isolating the effects of either FAR, GSI, or the street network orientation. In conclusion, we can assume that it would contribute to the footfall potential if the designed streets align with the existing street network.

4. Summary, Conclusion, and Future Research Work

The comprehensive framework gives insights on how sustainable a design option is based on the input geometry. One can visualize all performance indicators at the same time and understand the trade-offs better. Additionally, importance weighting can be implemented to each metric so that the framework adapts accordingly to the project's challenges and goals. A notable advantage of the framework is that it can be used as a discussion table in participatory planning meetings since it could be easily adapted with interactive environments.

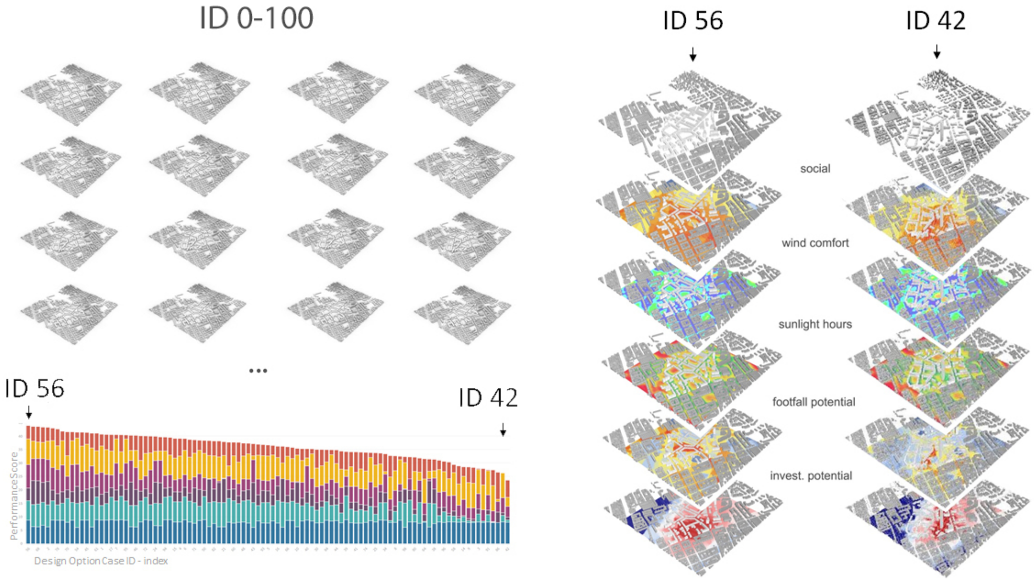

Figure 4. 101 Design cases, and their ranking based on the sum of all performance indicators in an equal weighing system. Each color represents one metrics, and the value from every metrics in a scale from 0-10 was added to the performance axis y. The best and worst performing design options are visualized in the right side of the figure. .

From the research, some general rules of thumb derived. First, people would have more access to liveable spots regarding the social dimension if we match and align the existing street network's orientation with the new design ones. Secondly, to perform better in terms of environment an urban layout should consist of diverse building typology and have a reasonable proportion between the built and non-built areas. On the other hand, while high and large buildings create wind shadow, at the same time, they block the sunlight. So, compromises should be made, and the optimum solutions based on the initial goals could assist which design is more sustainable for the location(This also includes weighting score for every performance indicator). As a general rule in the economic aspect, designed streets should align with the existing street network. However, this study could not define what exactly should be changed to have a design that would have higher investment potential. Similarly, the system sturdiness with the input parameters shows a high correlation. Still, it is hard to conclude since this correlation does not necessarily indicate impact, and further studies can be done on the topic.

As promising as the framework appears, it does not cover all issues related to measuring sustainability. However, it presumably is a supplement to the existing tools. There are several directions on how the framework could be augmented or improved:

1. Input parameters: only floor area ratio, ground space index, and street network orientation seem to be deficient in explaining the urban performance; additional

input parameters could be added.
2. Performance indicators: further research could be done in the economic dimension; its performance indicators could be tested in several real locations.
3. Data Analysis: simple linear correlations tend to be insufficient to explain some phenomena in the design's performance; therefore, multiple linear regression models, or MCDA-based models for assessment, can be applied to operationalize further the performance data.
4. Data filtering algorithms can be built, such as footfall potential in areas with dangerous wind speeds or similar approaches combining the results.

As promising as the framework appears, of course, it does not cover all issues related to measuring urban sustainability. And further study should be done because the topic itself is complex, and cities are complex structures, and the interdisciplinary field makes it complicated to come up with simple workflows.

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